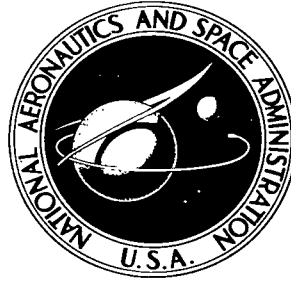


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# AN INVESTIGATION OF THE INFLUENCE OF AIRCRAFT TIRE-TREAD WEAR ON WET-RUNWAY BRAKING

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

Wet-runway braking tests were conducted at the Langley landing-loads track in which smooth and dimple-tread tires were used to represent completely worn tires. Five circumferential grooves were then cut into the tires to depths representing varying degrees of tread wear. Two types of wear were simulated: uniform wear with all grooves cut to the same depth, and nonuniform wear with the center groove wearing completely smooth while significant depths remain in the outer grooves. For comparative purposes tests were made on dry and damp concrete surfaces and through water depths of 1 inch. On the wet runway, a gradual degradation in braking effectiveness was experienced up to about the 80-percent-worn tire-tread condition, where the wet-runway friction coefficients dropped markedly. The completely worn tire was observed to develop, at the higher speeds, only about one-half the braking effectiveness of a new tire.

INTRODUCTION

Previous tire research, as exemplified by references 1 and 2, has indicated that the wet-runway braking effectiveness of an aircraft tire is highly dependent on the original tire-tread design. An important corollary to this fact is that even a good tread design may lose effectiveness as the tire becomes worn through normal use. It was the primary purpose of this investigation to determine at what degree of wear a tire tread begins to lose braking effectiveness and to aid in determining when the tire should be removed most economically from service without compromising safety requirements.

TEST APPARATUS AND PROCEDURE

Test Facility

The investigation was conducted at the Langley landing-loads track, which has been used for several years to investigate many different facets of the

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\*Some of the material presented in this report was originally presented at the 1st AIAA Annual Meeting at Washington, D.C., June 29-July 2, 1964, in a paper by the authors entitled "Effects of Tread Wear on the Wet Runway Braking Effectiveness of Aircraft Tires."

landing and ground-handling problems of aircraft. The landing-loads track, as shown schematically in figure 1, consists of a large hydraulic water-jet catapult which accelerates the 60-foot-long test carriage (fig. 2) to speeds up to 120 knots. A complete description of the catapult system is given in reference 3 and a description of the operation of the track, in reference 4. Close control of such test parameters as forward speed, sinking speed, vertical load, and runway-surface condition coupled with versatile instrumentation capabilities permits a detailed independent investigation of each of the many variables affecting landing-gear and tire performance. Excellent repeatability of test conditions can also be achieved for purposes of comparison and control.

### Tires Tested

In the tests  $32 \times 8.8$ , type VII, 22-ply-rating aircraft tires were used. One was a specially molded smooth tire and the others were standard dimple-tread and three-groove tires. Tire-tread wear was simulated by using the smooth and dimple-tread tires to represent completely worn tires and then cutting progressively deeper grooves into the tire treads to simulate various wear conditions. Five circumferential grooves were cut into all the tires with the saw and jig arrangement shown in figure 3. The saw was held rigidly in a special fixture, and an adapter plate on the bottom of the saw permitted close control of groove depth.

Photographs of the tires tested are shown in figure 4. The dimple-tread tire (tire I, fig. 4(a)) was grooved to represent nonuniform tread wear, as suggested by airline experience of tire wear, with the center groove wearing at a faster rate than the outer grooves. The smooth tire (tire II, fig. 4(b)) was grooved to simulate uniform tread wear, with all grooves wearing evenly. After the uniform 20-percent-worn tread was tested, it was judged unsafe to cut the grooves as deeply as necessary to represent a new tire; therefore, a standard three-groove fighter-airplane tire (tire III, fig. 4(c)) was modified by cutting two additional grooves to represent a new five-groove tire. Groove depths for all tires were measured and recorded before and after each test with both a micrometer depth gage and a dial indicator. The depth of each groove was measured at approximately the same location in six different places around the circumference of the tire. The average depths recorded for each groove and the tolerances maintained are shown in table I. Tire footprints were also taken at each wear point.

### Test Conditions

Most of the tests were made on a wet runway for a tire pressure of 150 psi. The test section of the track was provided with a sprinkler system to achieve essentially constant wetness which because of runway unevenness varied in the test section from 0.1 to 0.3 inch of water. Some tests were made for a tire pressure of 90 psi, both on the wet runway and on a runway covered with 1 inch of water. The static vertical load on the tire for all runs was 10 500 pounds. Magnetic pickups placed at intervals along the track initiated braking cycles and controlled the number and location of these cycles for each run. Pressure was metered to the brake through a micrometer needle valve, which acted as a controllable orifice. This metering was done so that brake-pressure rise time

could be varied with the forward speed and anticipated friction conditions to give approximately the same braking distance per run. Several tests were made with the new five-groove tire on a damp surface, in which the surface closely resembled a runway as it might be in the early morning following a heavy dew with no puddles or standing water. A few tests were made on dry concrete to provide comparative data for other braking conditions.

The test tires were mounted in the special test fixture shown schematically in figure 5, which is the same one used in previous investigations (refs. 1, 2, and 5). The vertical load and drag load were measured at the axle, and errors due to the inertia of the lower mass were corrected by accelerometers. These corrected values were used to compute the true instantaneous tire-ground friction coefficients throughout the entire brake cycle. Also recorded were wheel angular displacement, velocity, and acceleration; brake torque and brake pressure; wheel vertical displacement; and carriage forward velocity.

## TEST RESULTS

Instantaneous braking-friction coefficients were computed for all braking cycles from a freely rolling wheel to a locked wheel. However, the braking-effectiveness test results discussed in this paper are expressed in terms of  $\mu_{AV}$ , the average friction coefficient developed between a slip ratio of 0.1 to 0.5 (shown schematically in fig. 6). The presentation of data in this manner tends to smooth any uncharacteristic peaks or low points in individual brake cycles which may be caused by localized slippery spots or runway contaminants. As indicated in figure 6, the curve of friction coefficient  $\mu$  as a function of slip ratio for wet runways flattens out, so that the average friction coefficient  $\mu_{AV}$ , the maximum friction coefficient  $\mu_{MAX}$ , and the skidding friction coefficient  $\mu_{SKID}$  all tend toward a common value. The average friction coefficient is also more likely to be the overall friction coefficient obtained with modern antiskid systems.

### Tire-Wear Effects

Previous experience (ref. 1) had suggested little difference in wet-runway braking effectiveness between smooth and dimple-tread tires, a conclusion supported by the results shown in figure 7 where tire I (dimple) and tire II (smooth) are compared before any grooves were cut.

Nonuniform wear.- Figure 8 summarizes the results of the nonuniform-wear investigation in which the dimple tire was used. Friction coefficients for all wear points drop rapidly with increasing forward speed, with the worn tire developing only about one-half the friction of the new tire at the higher speeds. It should be recalled that when the nonuniformly worn tire is 100 percent worn, only the center groove is worn smooth while significant groove depths remain in the outer grooves, as shown in table I. This fact accounts for the relatively high friction levels at this wear condition as compared with the results obtained for the ungrooved dimple-tread tire. The effect of tread wear

is illustrated more clearly in figure 9, where a gradual degradation in braking effectiveness is noted as the wear progresses from a new tire to about the 80-percent-worn tire-tread condition. Further tread wear noticeably reduces the braking-friction levels at all velocities, with as much braking effectiveness being lost between the 80- and 100-percent-worn tire-tread condition as was lost between the 0- and 80-percent-worn condition.

Uniform wear.- The trends noted in the nonuniform-wear investigation were also observed in the uniform-wear investigation; these results are summarized in figure 10. As in the nonuniform-wear case, a noticeable decline in braking effectiveness occurs near the 80-percent-worn tire-tread condition. As previously mentioned, total tire tread wear prevented regrooving tire II beyond the 20-percent-worn tire-tread condition, but apparently the results would follow the trend in figure 9, with very little change in braking effectiveness occurring between the 0- and 20-percent-worn conditions.

A possible explanation of the poor braking performance of a worn tire is offered in figure 11, where the tire footprints taken at the five highest uniformly worn conditions are shown. In taking the tire footprint, the entire lower surface of the tire was covered with chalk, including the grooves. The tire was then lowered onto a piece of paper stretched over an aluminum plate, and allowed to settle until full static vertical load was attained. The footprint taken at the 95-percent-worn condition (fig. 11(b)) shows heavy evidence of chalk in all five grooves; this indicates that tire deformation has, in effect, eliminated the grooves at this wear condition. At the 90-percent-worn condition (fig. 11(c)) slight chalking is still evident in all grooves, whereas at the 85-percent-worn condition (fig. 11(d)) chalking is found in the outer grooves only. The tire shows no evidence of chalking in the grooves at the 80-percent-worn condition (fig. 11(e)), and it is at this percent of tread wear, as shown previously in figure 10, that tire performance begins to deteriorate most rapidly with increasing wear. Thus, it seems that the effects on braking performance of the degree of tread wear of a tire cannot accurately be gaged by eye, since a continuous tread pattern is visible in figure 11 even at the 95-percent-worn condition although the tire behaves very much like a smooth tire during braking.

Tire spin-up.- Excessive tire-tread wear can greatly increase the time required for the wheel to spin up following brake release, as shown in figure 12. Spin-up time in this figure is understood to be the elapsed time between brake release following a full skid and the achievement of equivalent free-roll forward velocity. Spin-up time for the new tire on a dry runway is seen to be below 0.1 second for all forward velocities, whereas the addition of water to the runway more than doubles the spin-up time for this tire at the higher velocities. As shown in figure 12, spin-up time at the higher velocities increases rapidly with increasing tread wear. For example, at 40 knots the 100-percent-worn tire requires about 0.1 second for spin-up, whereas at 80 knots the same tire requires a full second for spin-up. In many of the high-speed tests with the smooth tire, spin-up following brake release never occurred within the limited length of the test track. The reason for the long spin-up times noted is, of course, due to the extremely low friction coefficients developed under these conditions. It is of interest to note the magnitude of the time increase, however.

## Other Effects

Groove configuration.- Because of slight differences in the tire-grooving technique and the different tires used, the groove widths and groove locations differed for the various tires tested. The importance of the difference in groove width is shown in figure 13. Tire III having a nominal groove width of 0.375 inch developed notably better friction coefficients at all speeds than the nonuniformly 0-percent worn tire I, which had a nominal groove width of 0.290 inch. Although tire III had somewhat deeper grooves than tire I (table I), it is believed that the groove width was the primary factor responsible for the increased braking friction, since the average water depth (0.2 inch) in both tests was less than the average groove depth. This conclusion is further supported in figure 13 by comparing the braking effectiveness for the nonuniformly 50-percent-worn tire I (nominal groove width of 0.290 inch) with that for the uniformly 60-percent-worn tire II (nominal groove width of 0.220 inch), which had about the same groove depth in the three center grooves. The improved wet-runway braking effectiveness of the wider groove is probably a result of better or more rapid escape of water from the footprint region and of higher local tire-ground bearing pressures.

Although the grooves were cut into the tires symmetrically spaced about the center groove, small differences did exist in the groove spacing between tires, as shown in figure 14. These differences are thought to have less of an effect on braking performance than groove width. Tire III, a modified production tire, also had grooves of different shape, as shown schematically in figure 14(c), with the three central grooves having a rounded shape, whereas the other two grooves in this tire and all grooves in the other tires were rectangular. It is uncertain what effect this change in shape may have, but there is an obvious need for further investigation of the effects of tire groove width, spacing, and shape in hopes of optimizing tire-tread design.

Tire-inflation pressure.- Figure 15 shows the effects of tire-inflation pressure on braking effectiveness on dry and wet runways. The lower tire pressure (90 psi) resulted in somewhat higher friction coefficients on dry-runway braking, an effect previously noted in reference 1. On wet-runway braking, however, only slight differences were observed between the two tire pressures.

Shallow water.- Small amounts of water on the runway can have a significant effect on braking effectiveness. Figure 16 illustrates the loss in braking effectiveness of tire III for an inflation pressure of 90 psi, caused by a damp runway such as might be found early in the morning following a heavy dew. One run was actually made under these conditions, shown by the solid symbols in this figure. Such conditions were simulated for the rest of the test by wetting the runway and then brushing off all standing water. Also included for comparison in this figure are the results for tire III braking on a wet runway, with water depth ranging from 0.1 to 0.3 inch. Braking-effectiveness test results for tire III for an inflation pressure of 150 psi show the same trends (fig. 17).

Rolling resistance.- Free-rolling resistance force was measured for tire III on dry, damp, and wet concrete surfaces and the results are presented in figure 18. A straight line is faired through the dry-runway values for the two tire pressures investigated (90 and 150 psi) and, as might be expected, a

somewhat higher rolling resistance is obtained for the lower tire pressure. It is of interest to note the effect of runway-surface condition on rolling resistance. Somewhat lower rolling resistance is obtained on the damp runway surface than on the dry surface, undoubtedly because of lubrication by the water film; however, higher rolling resistance is obtained on the wet surface (water depth 0.1 to 0.3 inch) and must be due to fluid drag on the tire.

Deep water.- In order to explore the effects of tire-tread wear on tire hydroplaning (ref. 6) and on braking in deep water, tests were made concurrently with the aforementioned tests but with a water depth of 1 inch. In these tests, with a tire inflation pressure  $p$  of 90 psi, the tire was allowed to roll freely for a time before the brakes were applied to determine the magnitude of the fluid-displacement drag created on the tire. The results of the free-rolling portion of the investigation are shown in figure 19 and indicate that tire-tread depth has no discernible effect on fluid-displacement drag. The tire-hydroplaning-velocity equation, developed in reference 6 and shown in figure 19, is substantiated by the results as indicated by the peak in fluid drag and by tire spin-down (denoted by the flagged symbols). It should be noted that the fluid drag shown in this figure is incremental fluid drag - that is, the rolling resistance shown in figure 18 has been subtracted out to give only the added drag due to fluid displacement by the tire.

The effect of tread wear when braking in deep water is shown in figure 20. This figure indicates a very definite drop in braking effectiveness in 1 inch of water as tire wear progresses past the 60-percent-worn tread condition. The much higher friction levels developed by the new tire is due, as previously explained, to the wider grooves in the tire. For all wear conditions, however, the friction coefficient reaches a minimum at or near the tire hydroplaning speed  $V_p$ . The apparent friction coefficients of figure 20 include the effects of fluid-displacement drag. In order to determine the contribution of the brake itself, the fluid-displacement drag must be subtracted as illustrated in figure 21 for tire III. The net retarding effect of the brake at hydroplaning speeds is seen to be at a level comparable to the free rolling resistance of the tire (fig. 18), which would indicate that while attempting to brake at speeds in excess of tire hydroplaning speeds, the retardation developed on an aircraft must come from sources other than braking friction.

#### CONCLUDING REMARKS

This investigation has demonstrated the important effects of tire-tread wear on the wet-runway braking effectiveness of aircraft tires. For the two types of tread wear that were simulated - that is, uniform and nonuniform wear - gradual degradation in braking effectiveness was experienced as tread wear progressed from a new tire, or 0-percent-worn condition, to a 60- to 80-percent-worn tire. As tread wear passed the 80-percent-worn condition, however, braking effectiveness dropped markedly. These results indicate that aircraft tires should be replaced before the tread is worn completely smooth if safety



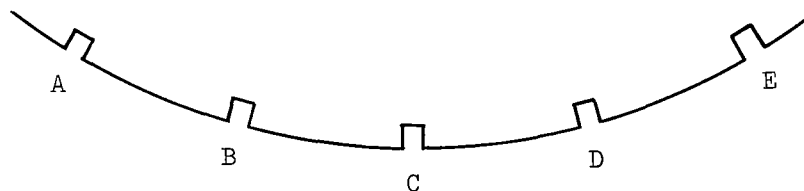
requirements are not to be compromised. Further study of the depth, width, spacing, and shape of tire grooves is needed in order to optimize wet-runway braking effectiveness.

Langley Research Center,  
National Aeronautics and Space Administration,  
Langley Station, Hampton, Va., February 2, 1965.

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3. Joyner, Upshur T.; and Horne, Walter B.: Considerations on a Large Hydraulic Jet Catapult. NACA TN 3203, 1954. (Supersedes NACA RM L51B27.)
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5. Horne, Walter B.; Joyner, Upshur T.; and Leland, Trafford J. W.: Studies of the Retardation Force Developed on an Aircraft Tire Rolling in Slush or Water. NASA TN D-552, 1960.
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TABLE I.- GROOVE DIMENSIONS FOR TIRES INVESTIGATED



Tread wear, percent	Desired depth, in., for groove -					Average depth, in., before tests for groove -					Average depth, in., after tests for groove -					Av. groove width, in.
	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	
(a) Tire I (dimple tread, nonuniform wear)																
0	0.250	0.250	0.250	0.250	0.250	0.199	0.227	0.212	0.202	0.195	0.189	0.216	0.198	0.190	0.184	0.290 ↓
50	.216	.155	.125	.155	.216	.206	.150	.120	.137	.203	.195	.136	.104	.126	.192	
80	.194	.098	.050	.098	.194	.185	.098	.047	.103	.183	.177	.093	.037	.094	.172	
90	.175	.094	.037	.094	.175	.177	.093	.037	.094	.172	.170	.088	.032	.087	.168	
100	.073	.059	0	.059	.073	.071	.052	0	.051	.072	.058	.043	0	.041	.053	
(b) Tire II (smooth tire, uniform wear)																
20	0.192	0.192	0.192	0.192	0.192	0.188	0.193	0.192	0.193	0.187	0.180	0.186	0.186	0.186	0.179	0.220 ↓
60	.144	.144	.144	.144	.144	.142	.150	.145	.136	.135	.138	.147	.142	.130	.130	
75	.060	.060	.060	.060	.060	.064	.066	.064	.073	.061	.059	.060	.060	.068	.060	
80	.048	.048	.048	.048	.048	.049	.045	.049	.047	.046	.044	.040	.044	.040	.040	
85	.036	.036	.036	.036	.036	.036	.039	.039	.043	.036	.029	.035	.035	.038	.033	
90	.024	.024	.024	.024	.024	.024	.023	.024	.024	.023	.021	.018	.022	.020	.020	
95	.012	.012	.012	.012	.012	.015	.015	.016	.015	.016	.010	.010	.010	.010	.010	
100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	----- ↓
(c) Tire III (new tire, uniform wear)																
0	0.240	0.240	0.240	0.240	0.240	0.242	0.242	0.238	0.235	0.241	0.230	0.230	0.225	0.223	0.230	0.375

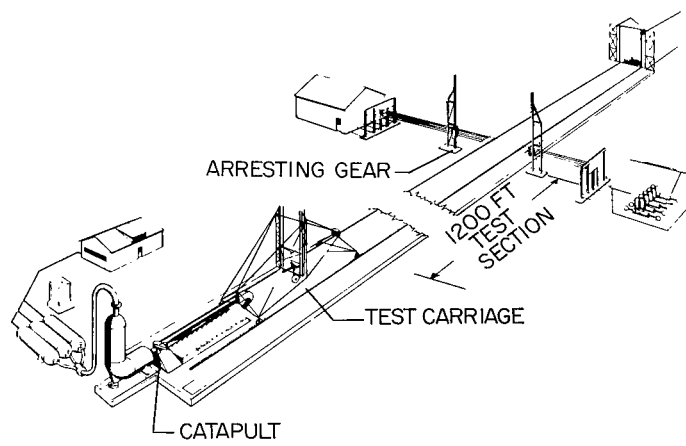
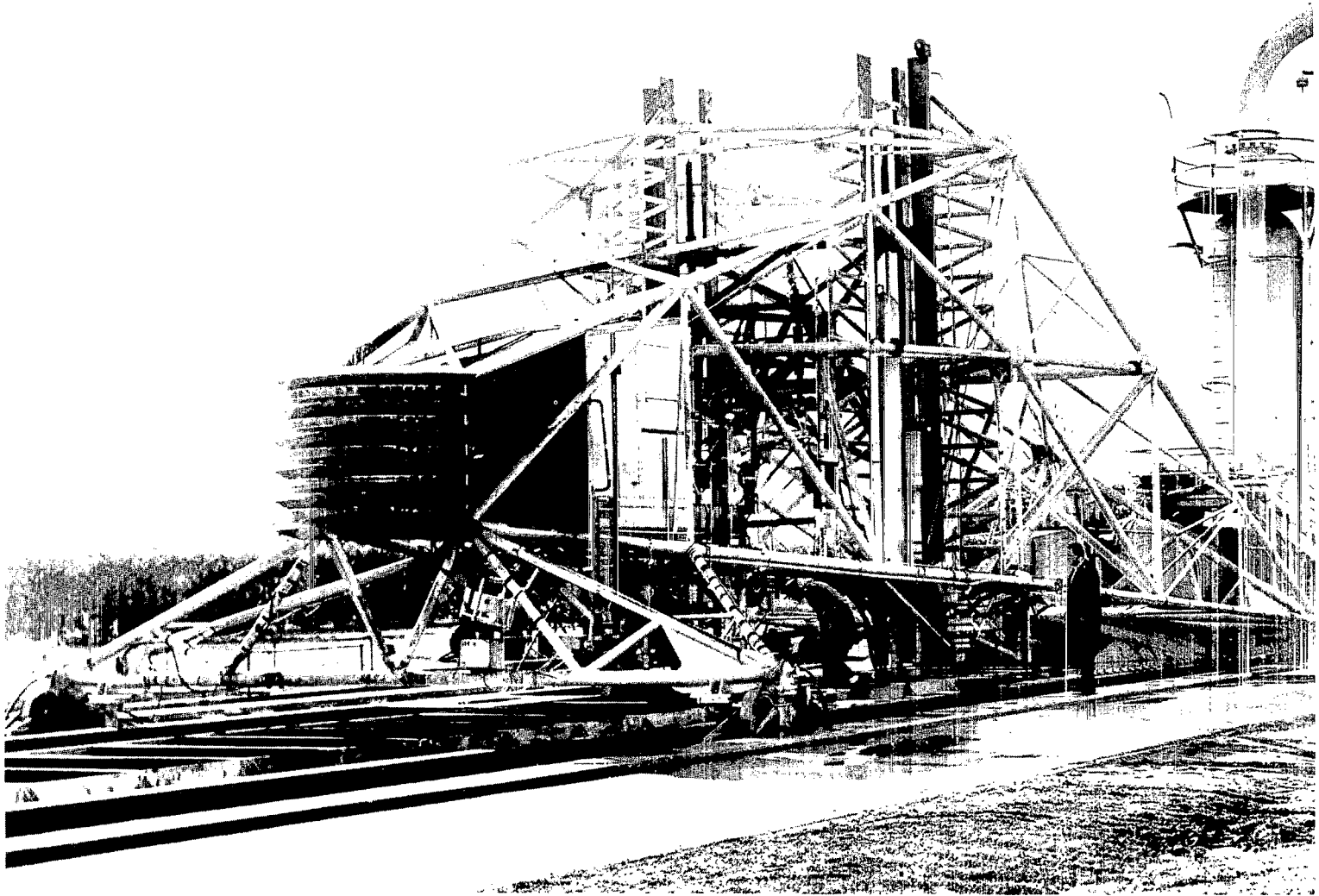
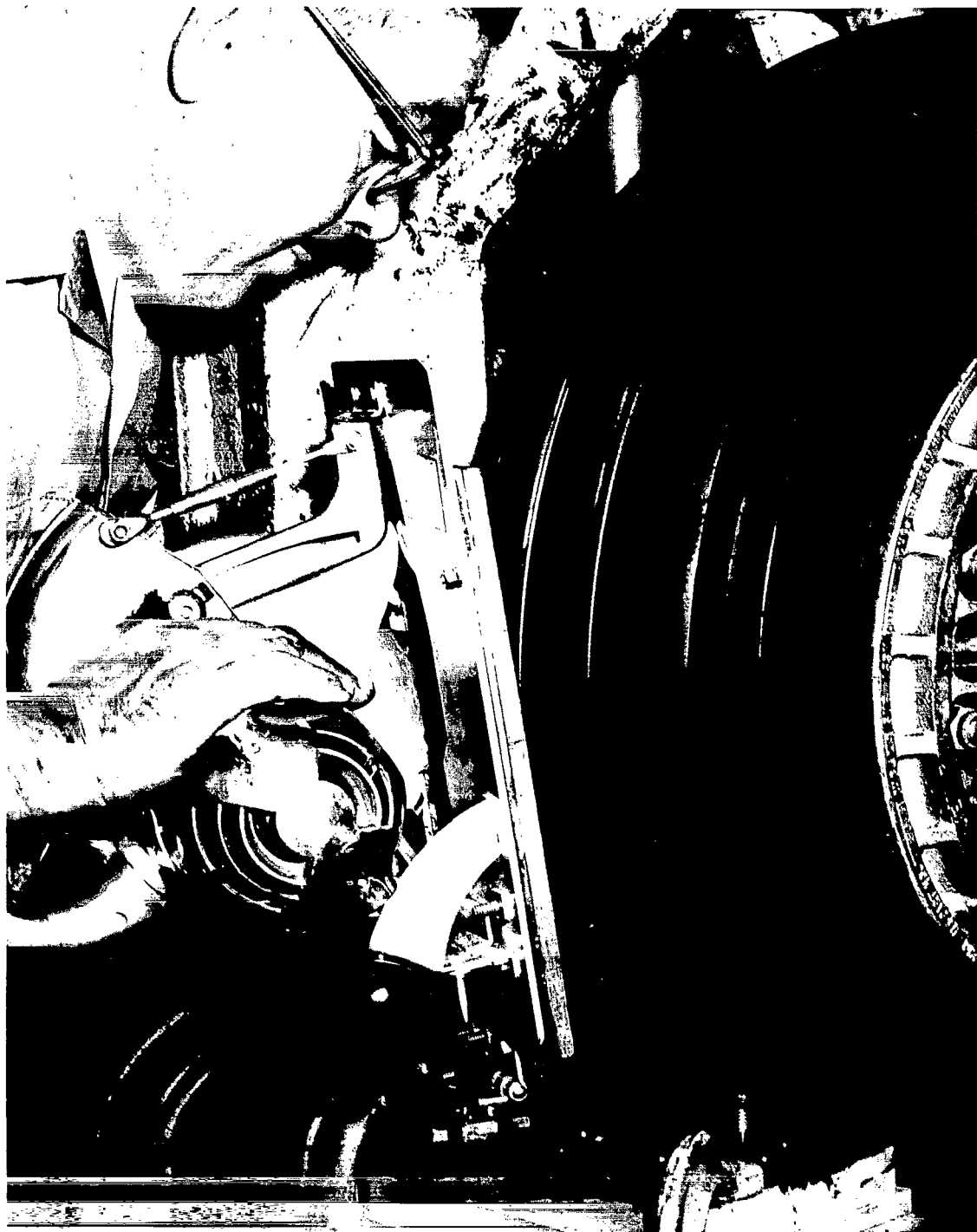


Figure 1.- Schematic of Langley landing-load track.



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Figure 2.- Main test carriage at Langley landing-loads track, with catapult in background.



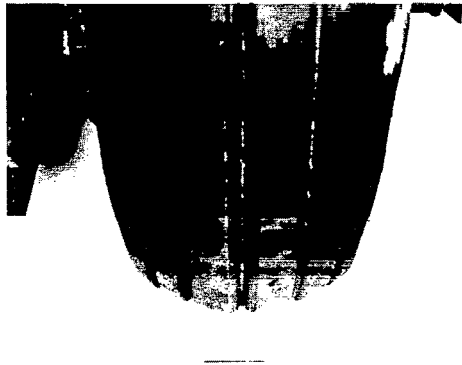
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Figure 3.- Saw and jig arrangement used for grooving all test tires.



(a) Tire I (dimple-tread tire) before and after grooving.



(b) Tire II (smooth tire) before and after grooving.



(c) Tire III (new tire). L-65-33

Figure 4.- Tires used in tread-wear investigation.

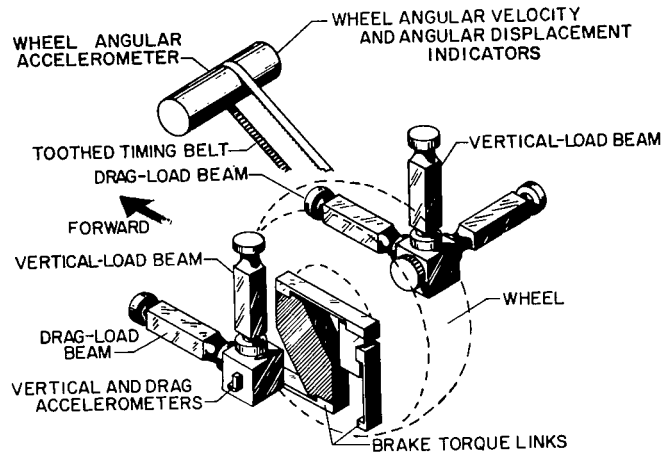


Figure 5.- Schematic of test fixture used for all tires.

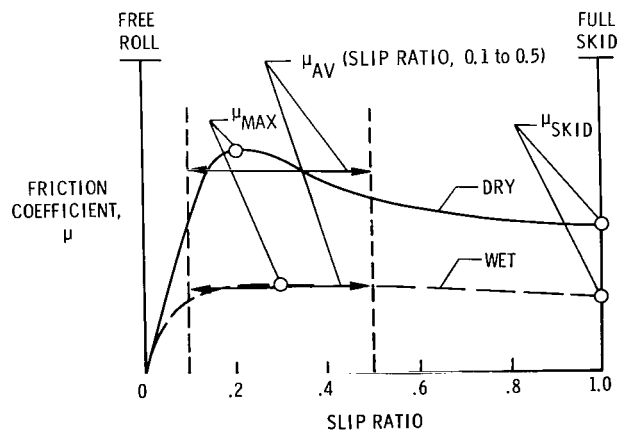


Figure 6.- Schematic comparison of various friction coefficients, showing how  $\mu_{AV}$  was derived.

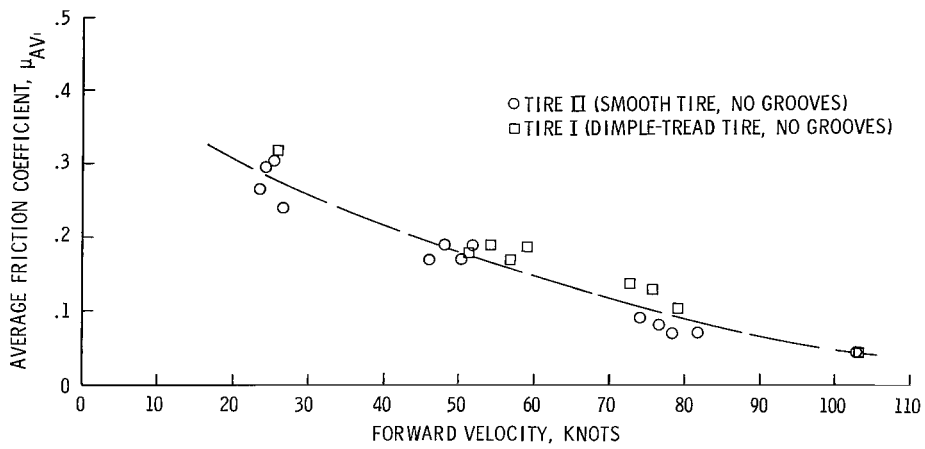


Figure 7.- Wet-runway braking effectiveness of smooth and dimple-tread tires.  
 Tire pressure, 150 psi.

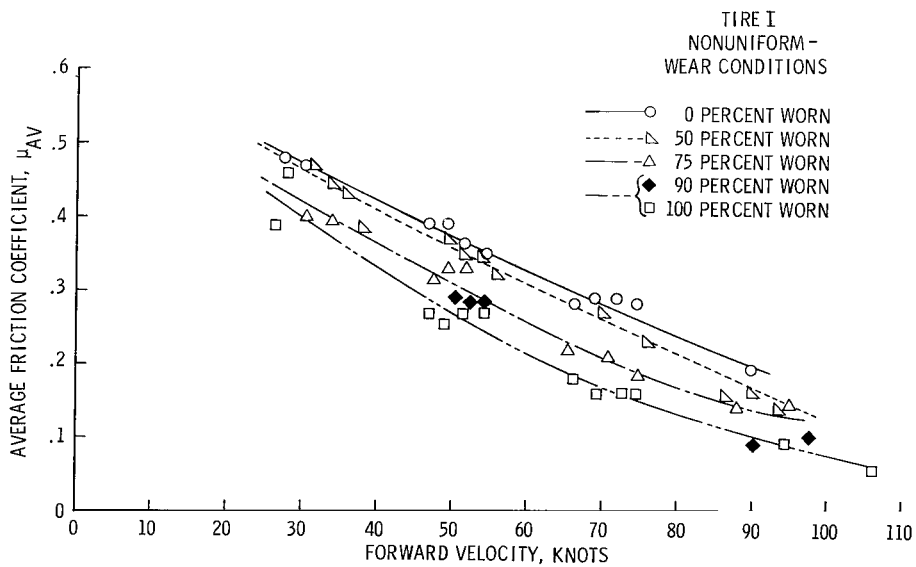


Figure 8.- Effects of nonuniform tread wear and forward velocity on wet-runway braking effectiveness. Tire pressure, 150 psi.



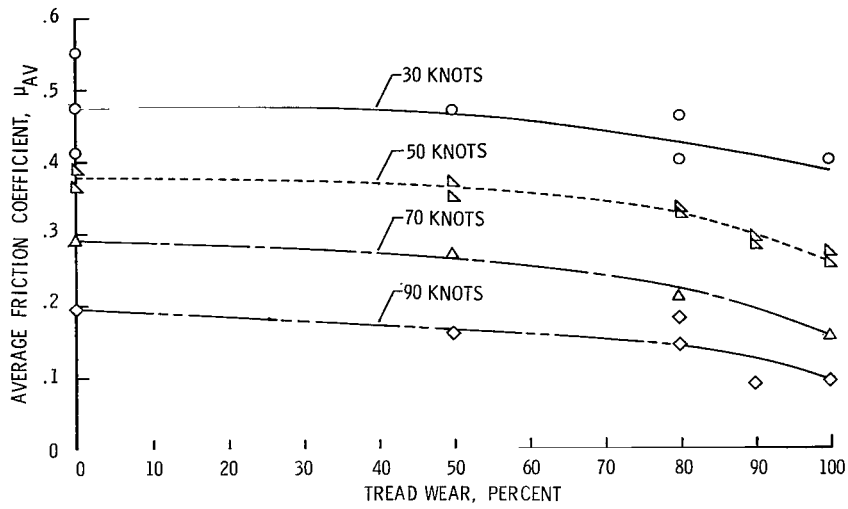


Figure 9.- Effects of nonuniform tread wear on wet-runway braking effectiveness at selected velocities for tire I. Tire pressure, 150 psi.

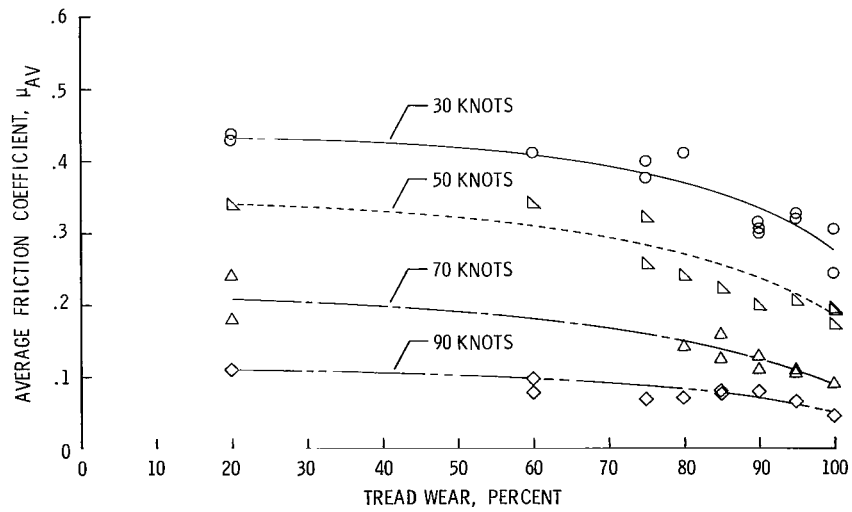
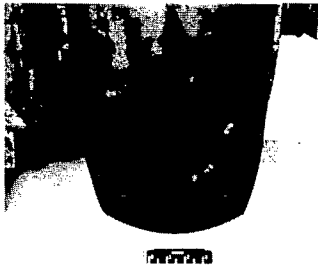
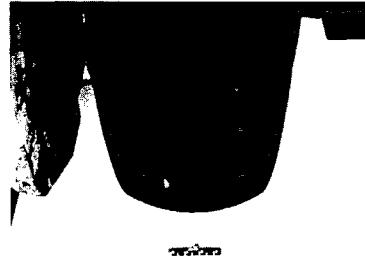


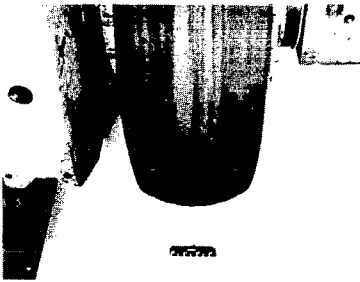
Figure 10.- Effects of uniform tread wear on wet-runway braking effectiveness at selected velocities for tire II. Tire pressure, 150 psi.



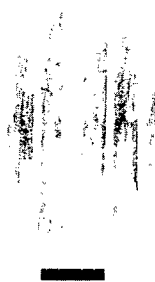
(a) 100 percent worn.



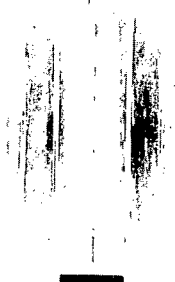
(b) 95 percent worn.



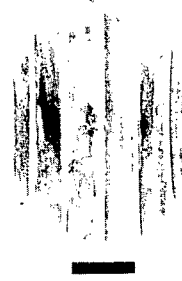
(c) 90 percent worn.



(d) 85 percent worn.



(e) 80 percent worn.



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Figure 11.- Photographs of tire footprints and tire profiles at various conditions of uniform tread wear. Tire 11.

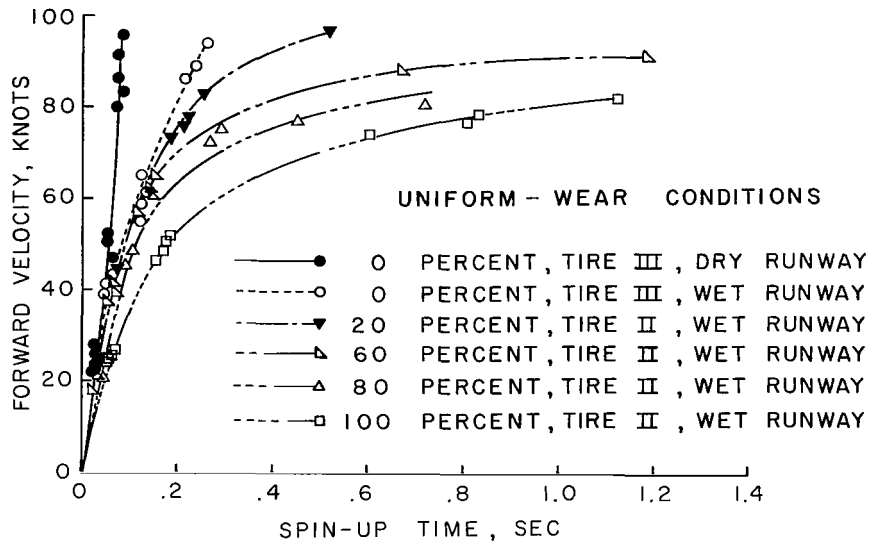


Figure 12.- Effects of uniform tread wear on tire spin-up time following brake release.  
Tire pressure, 150 psi.

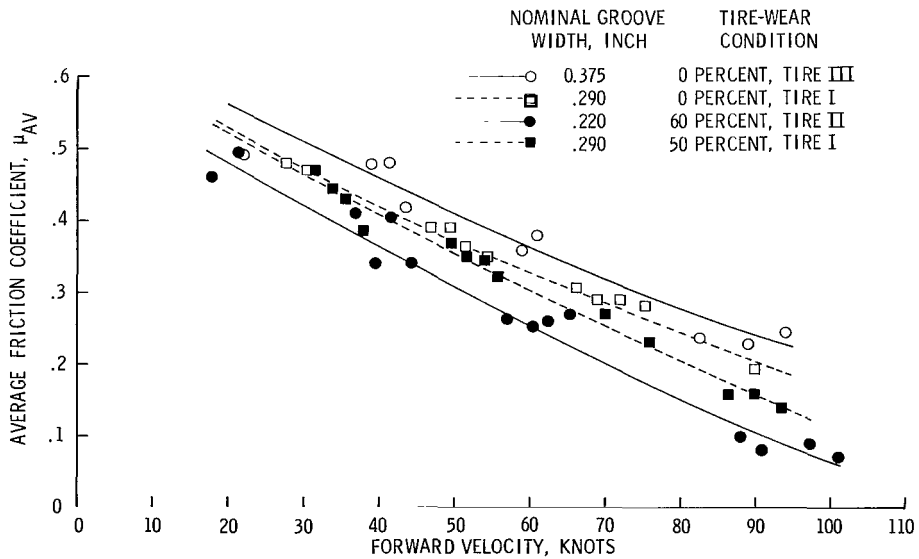
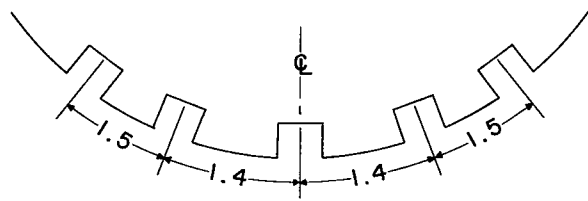
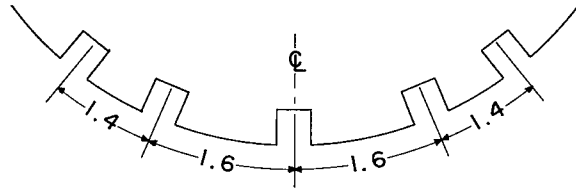


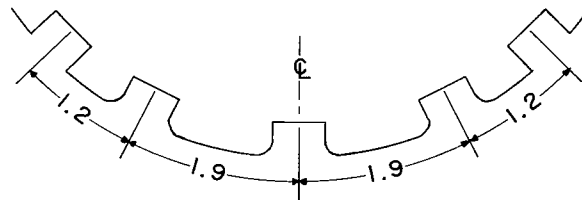
Figure 13.- Effects of tire-groove width on wet-runway braking effectiveness.  
Tire pressure, 150 psi.



(a) Tire I, nonuniform wear.



(b) Tire II, uniform wear.



(c) Tire III, new tire.

Figure 14.- Schematic cross sections of tires tested showing spacing of grooves. (All dimensions are in inches. Drawing not to scale.)

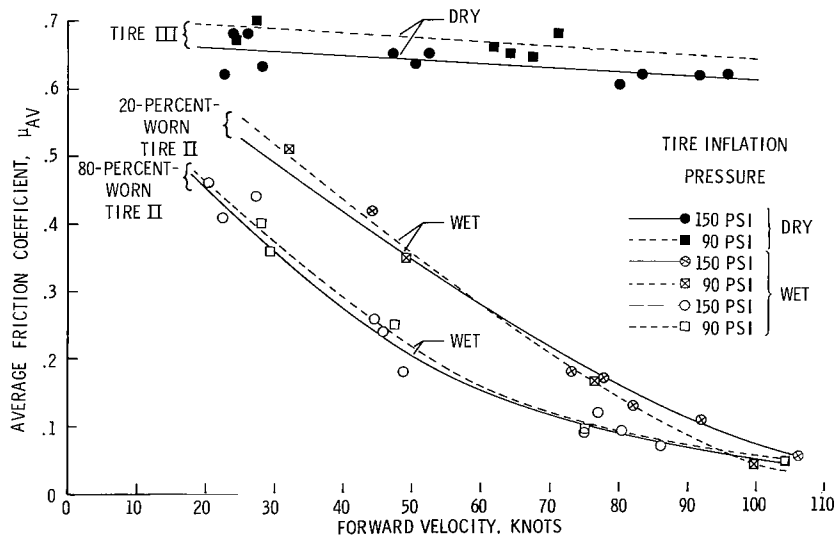


Figure 15.- Effects of tire inflation pressure on dry- and wet-runway braking effectiveness at selected uniform-wear conditions.

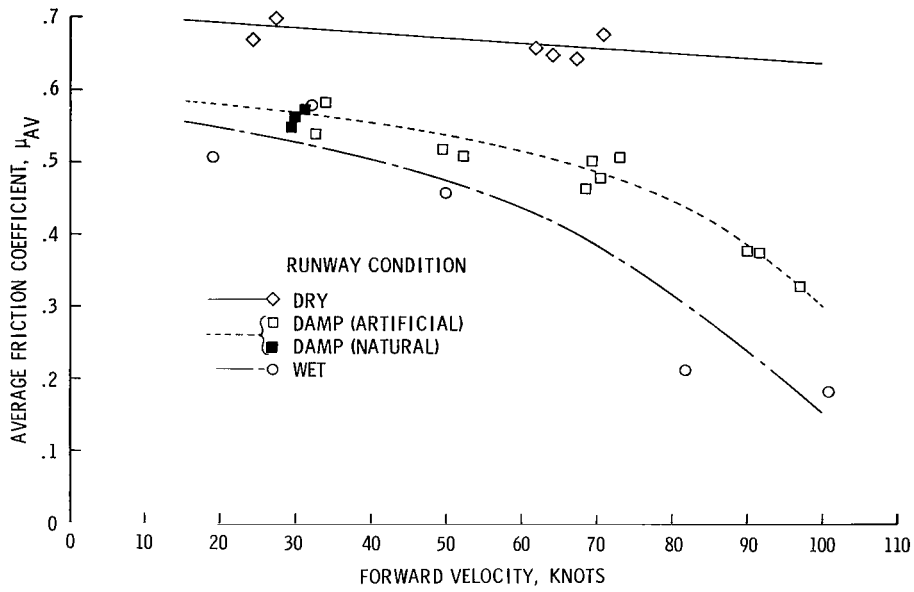


Figure 16.- Effects of runway-surface condition on the braking effectiveness of tire III.  
Tire pressure, 90 psi.

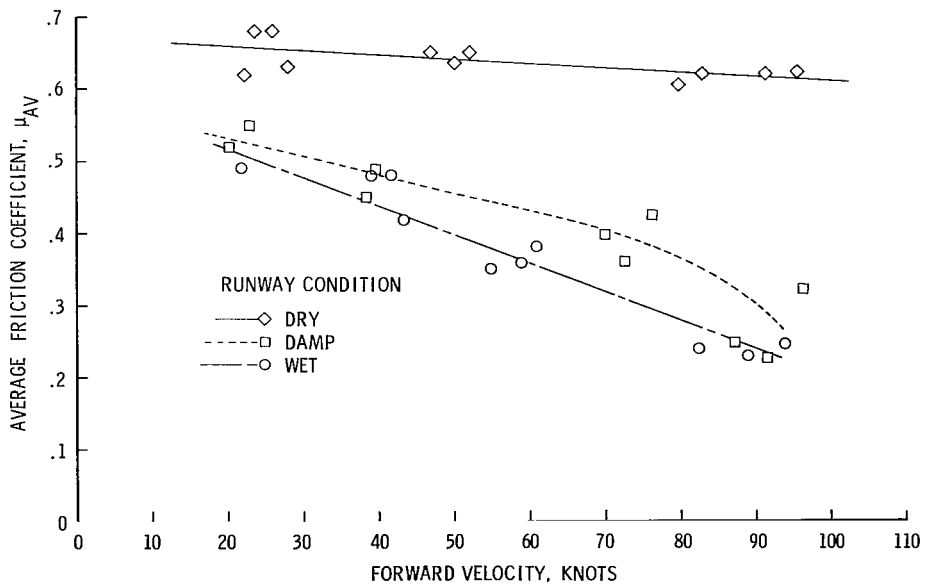
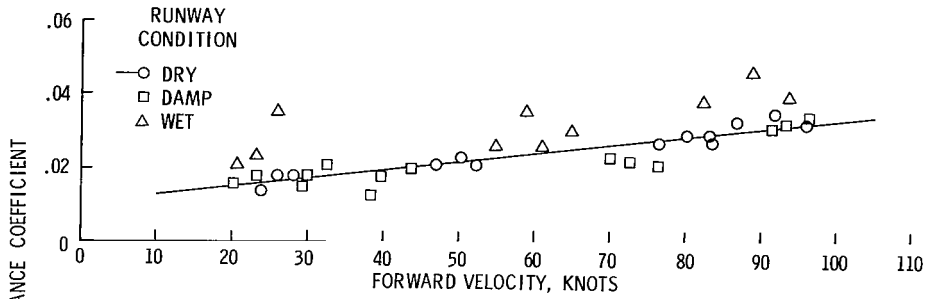
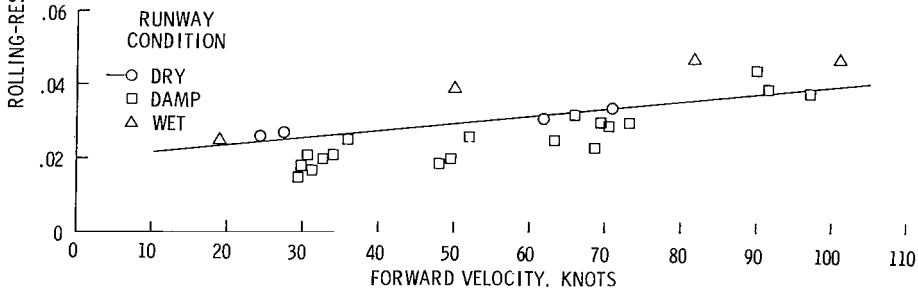


Figure 17.- Effects of runway-surface condition on the braking effectiveness of tire III.  
Tire pressure, 150 psi.



(a) Tire inflation pressure, 150 psi.



(b) Tire inflation pressure, 90 psi.

Figure 18.- Effect of tire inflation pressure and runway-surface condition on the rolling resistance of unbraked tire III.

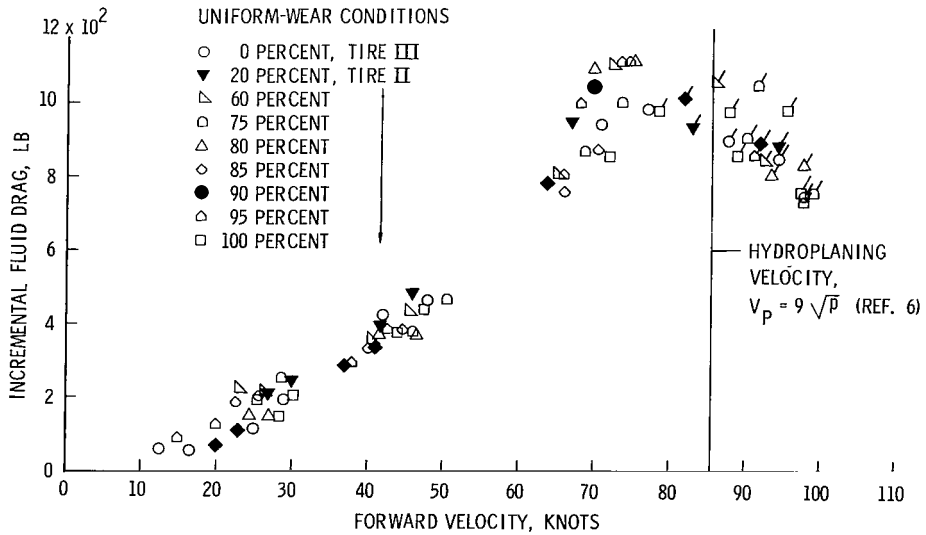


Figure 19.- Fluid-displacement drag developed by a tire rolling unbraked through water 1 inch deep. Tire pressure,  $p$ , 90 psi. (Flagged symbols denote tire spin-down.)

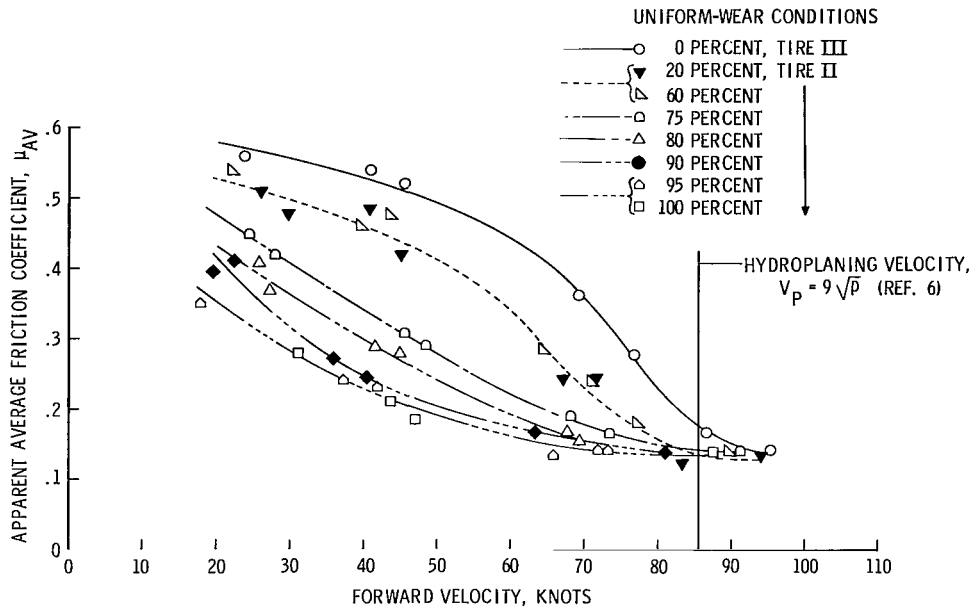


Figure 20.- Effect of uniform tread wear on the braking effectiveness of a tire in water 1 inch deep. Tire pressure,  $p$ , 90 psi.

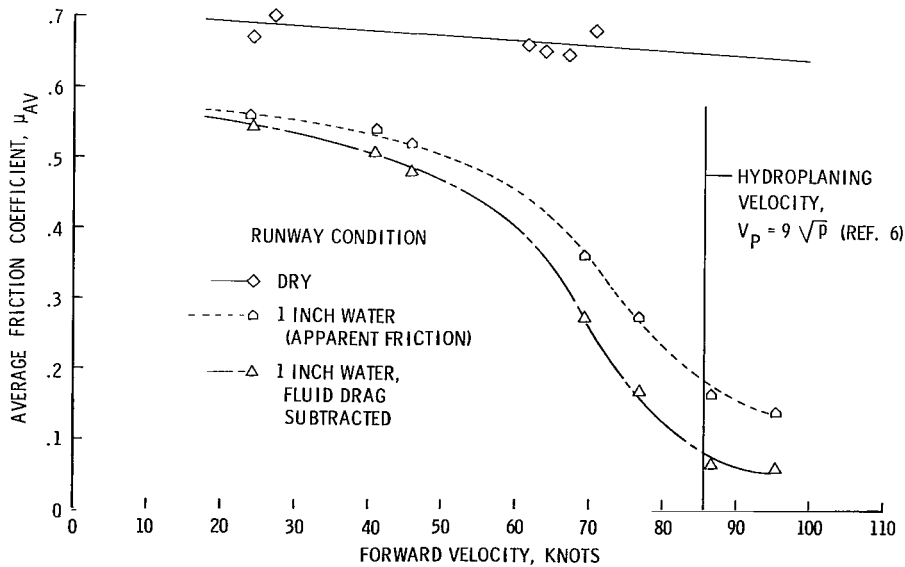


Figure 21.- Comparison of apparent and actual friction coefficients developed by tire III braking in water 1 inch deep. Tire pressure,  $p$ , 90 psi.